Stark Tuning of Donor Electron Spins in Silicon

F. R. Bradbury[1], Alexei M. Tyryshkin[1], Guillaume Sabouret[1], Jeff Bokor[2,3], Thomas Schenkel[2], S. A. Lyon[1]

[1]Department of Electrical Engineering, Princeton University, Princeton, NJ 08544
[2]E. O. Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[3]Department of Electrical Engineering and Computer Science, University of California Berkeley, CA 94720

Abstract. We report Stark shift measurements for ^{121}Sb donor electron spins in silicon using pulse electron spin resonance. Interdigitated metal gates on a Sb-implanted ^{28}Si epi-layer are used to apply the electric fields. Two quadratic Stark effects are resolved: a decrease of the hyperfine coupling between electron and nuclear spins of the donor and a decrease in electron Zeeman g-factor. A significant linear Stark effect is also observed, which we suggest arises from strain. We discuss the results in the context of the Kane model quantum computer.

Keywords: Electron spin resonance, silicon, donors, quantum computing, Stark effect
PACS: 71.79.Ej, 76.30.-v, 03.67.Lx, 71.55.Cn

INTRODUCTION

In the Kane architecture [1] of quantum computation (QC) qubits are envisioned to be encoded in spin states of donor impurities in a silicon lattice. This architecture is attractive because of the proven scalability of silicon devices and the long decoherence times measured for electron spins in silicon [2, 3]. While some aspects of the Kane architecture lie in the realm of existing silicon technologies, the scheme for single qubit operation was based on a theoretical estimate. To perform operations on single qubits, Kane proposed shifting the spin resonance with externally applied electric fields (Stark tuning). In this work, we present experimental proof of concept for Stark tuning the electron spin resonance (ESR) by resolving two quadratic Stark terms: a decrease in the hyperfine interaction and a decrease in the electron g-factor.

The donor electron spin-Hamiltonian is given by

$$\hat{H} = g\beta B_0 S_Z + a \cdot S_Z I_Z \qquad (1)$$

where the first term is the Zeeman interaction in applied field B_0, with g the electron g-factor and β the Bohr magneton, and the second term is the hyperfine interaction between electron (S) and nuclear (I) spins with hyperfine coupling constant, a. A Stark shift in the spin resonance energy may change the hyperfine coupling constant, a, or the electron g-factor.

METHODS

The sample used in this experiment is a ^{28}Si epi-wafer implanted with ^{121}Sb [4] (giving S = 1/2 and I = 5/2) and patterned with interdigitated metal top gates for the application of electric fields. Because the Stark shift of the donor ESR is smaller than the resonance linewidth (previously measured to be 0.2 MHz in isotopically-purified ^{28}Si [3]), this work extends a pulse ESR technique developed by Mims [5] which is sensitive to small changes in the ESR frequency. In our experiments, two X-band microwave pulses generate a Hahn echo signal from the donor spins. Electric field pulses applied to the donor spins using the interdigitated gates alter the resonance (precession) frequencies of the electrons spins, via the Stark effect, and thus produce a phase shift in the echo signal.

We extend Mims's experiment by introducing bipolar electrical pulse sequences to separate linear and quadratic Stark terms [6]. By flipping the sign of the applied electric field midway through the defocusing period of the Hahn experiment, precession phase shifts that depend asymmetrically on the field are refocused and only symmetric (quadratic to lowest order) Stark shifts are accumulated. Alternatively, pulses of opposite polarity and equal duration applied during the defocusing and refocusing periods will selectively detect only asymmetric (linear to lowest order) Stark shifts.

CP893, *Physics of Semiconductors, 28th International Conference*
edited by W. Jantsch and F. Schäffler

RESULTS AND DISCUSSION

Figures 1a and 1b display the echo phase shift in experiments designed to detect symmetric Stark effects. Measurements were taken on four hyperfine lines of the ^{121}Sb ESR spectrum corresponding to nuclear spin projections, $M_I = \pm 1/2$ and $\pm 5/2$. Fitting the echo phase shift with quadratic Stark terms required integrating over the ensemble of donor electron spins. The calculated curves for all plots were fit with the parameters $\eta_a = -3.7 \cdot 10^{-3}$ and $\eta_g = -1 \cdot 10^{-5}$ (in $\mu m^2/V^2$) where $\Delta g(E) = \eta_g \cdot g \cdot E^2$ and $\Delta a(E) = \eta_a \cdot a \cdot E^2$. Detailed discussions of these symmetric Stark experiments can be found elsewhere [6].

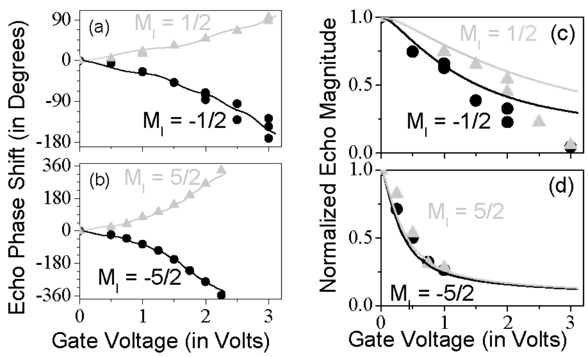

FIGURE 1. (a, b) Phase shift of the echo signal in symmetric Stark experiments and (c, d) decay of the echo magnitude in asymmetric Stark experiments as a function of the applied voltage across interdigitated gates for ^{28}Si:^{121}Sb at 6.2K and interpulse delay $\tau = 40\mu s$. Data (points) and numerical fits (lines) are shown.

In experiments designed to measure asymmetric Stark effects we observed no phase shift of the echo signal and only a reduction of its magnitude as shown in Figures 1c and 1d. In principle, tetrahedral symmetry at the donor site should prohibit the observed asymmetric Stark effects; however, interfacial strain and random defects can break this symmetry. Lattice mismatch strain in ^{28}Si epi-wafers similar to those used in this work has been evidenced in recent photoluminescence experiments [7] and strain in the silicon is known to shift the donor ESR [8]. Thinking of these intrinsic asymmetries as "effective" electric fields to which the real, applied field adds to (or subtracts from) we can fit the data in Figure 1c and 1d using the quadratic Stark terms. These fits assumed a Gaussian distribution of effective electric fields centered at zero with a standard deviation, $\sigma = 0.07$ V/μm .

It is interesting to compare the measured ESR linewidth with that calculated from the distribution of effective electric fields. The calculated linewidth is ~20kHz, an order of magnitude less than the measured resonance lines. Qualitatively, this supports the local strain explanation of the linear Stark effect. One effect of strain is to admix p-like hydrogenic donor states into the ground state wave function. This effect is analogous to that of an electric field and will give rise to the linear Stark term. More importantly, however, local strains also break the valley degeneracy in silicon and change the admixture of valley states, reducing the hyperfine interaction with the ^{121}Sb nucleus [8]. This term will not be affected by a long wavelength electric field and thus introduces broadening into the ESR line without contributing to the linear Stark effect.

CONCLUSIONS

The ability to Stark tune the spin resonance is an integral and previously unmeasured parameter for Kane model donor spin QC architectures. This study resolves quadratic hyperfine and g-factor Stark effects for ^{121}Sb donors in silicon. Spin resonance shifts are found to be small at the moderate electric fields used in this work; a maximum shift of 25 kHz was observed when average electric fields of ~0.1 V/μm were applied with $M_I = \pm 5/2$. This study also finds a significant linear Stark effect, which is consistent with strain-induced local asymmetries. Consequently, we suggest the importance of controlling strains for precise spin resonance tuning via the Stark effect.

ACKNOWLEDGMENTS

The authors would like to thank Igor Trofimov, Shyam Shankar, Rogerio de Sousa, Mark Friesen, Lloyd Hollenberg, and Cameron Wellard for helpful discussions. This research was supported at Princeton by the Army Research Office and the Advanced Research and Development Activity under Contract No. DAAD19-02-1-0040, and at Lawrence Berkeley National Labs by the National Security Agency under Army Research Office Contract No. MOD707501, the Department of Energy under Contract No. DE-AC02-05CH11231, and the National Science Foundation under Grant No. 0404208.

REFERENCES

1. B. E. Kane, Nature **393**, 133 (1998).
2. J. P. Gordon & K. D. Bowers, Phys. Rev. Lett. **1**, 368 (1958).
3. A. M. Tyryshkin *et al.*, Phys. Rev. B **68**, 193207 (2003).
4. T. Schenkel *et al.*, Appl. Phys. Lett. **88**, 112101 (2006).
5. W. B. Mims, Rev. Sci. Inst. **45**, 1583 (1974); W. B. Mims, Phys. Rev. A **133**, A835 (1964).
6. F. R. Bradbury *et al.*, cond-mat/0603324 (2006).
7. A. Yang *et al.*, Physica B **376-377**, 54 (2006).
8. D. K. Wilson & G. Feher, Phys. Rev. **124**, 1068 (1961).